The birefringent work of art "Gypsum figure," as viewed between crossed linear polarizers.

Courtesy of Univ. Ariz./A. Peinado

Russell Chipman
and Alba Peinado

The Mystery of the Birefringent Butterfly

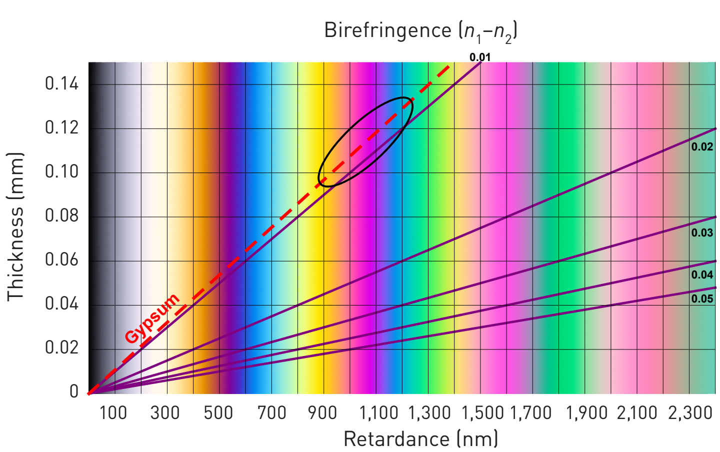
It’s the crown jewel of a collection of classroom materials housed at the University of Arizona’s College of Optical Sciences—a transparent butterfly slide that bursts into color when viewed through cross polarizers. These authors want to know: **Who is responsible for this striking work of art?**

Light polarization and birefringence, or double refraction, are often used to create beautiful works of art. The colorful butterfly, shown on the opening page between crossed polarizers, is a good example. It is a piece of historic birefringent art named *Gips-bild* (or Gypsum figure in English).

When a birefringent material is placed between crossed polarizers and illuminated with polychromatic light, one will see interference colors that depend on the variation of retardance with wavelength. Typically, the spectral variation of retardance is approximately proportional to the inverse of the wavelength. The resulting colors are represented in the Michael-Levy interference color chart. These interference colors are particularly saturated for retardances in the range of 500–1,300 nm; this is what creates the butterfly's vibrant colors.

Can you help us solve the case of the birefringent butterfly? After reading the article, please send any information you may have to opn@osa.org.

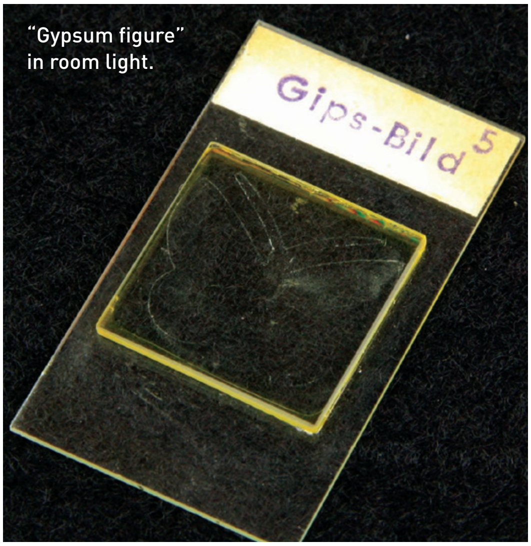
We were quite taken with the butterfly, and we have studied it carefully in the hopes of learning about its origin and construction.



Michael-Levy interference color chart

The chart shows the interference colors as a function of retardance, crystal thickness and birefringence (sloped purple lines). Most of the *Gips-bild* colors come from inside the ellipse.

Courtesy of Univ. Ariz./R. Chipman



"Gypsum figure" in room light.

Courtesy of Univ. Ariz./A. Peinado

Unfortunately, however, despite our best efforts, the artist or artists who fabricated the butterfly remains a mystery.

Can you help us solve the case of the birefringent butterfly? After reading the article, please send any information you may have to opn@osa.org.

Case notes

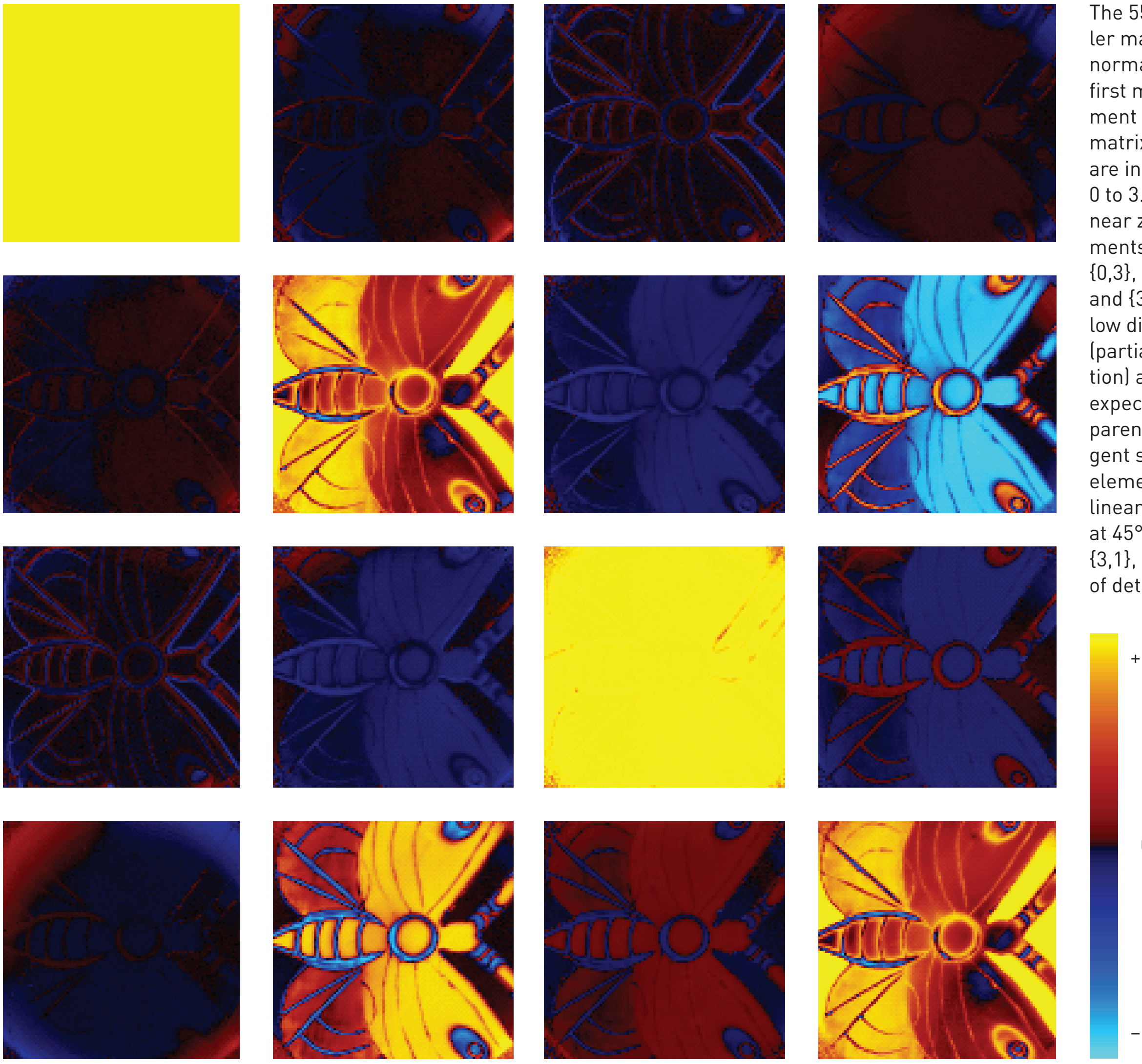
Who: The 2-cm^2 area of *Gips-bild* is obviously the work of someone who used meticulous and well-executed fabrication techniques; the butterfly is more striking than any other birefringent sample we have encountered.

What: The College of Optical Sciences at the University of Arizona, U.S.A., has a large collection of antique and historic telescopes, microscopes, lenses and cameras curated by Prof. John Greivenkamp. The equipment comes from some of the world's most respected instrument makers from the 18th century to the present, including Jesse Ramsden, John Dollond and Simon Plössl.

Within the collection is a Prado Universal Projector 250/500 from Leitz, which was purchased by Prof. William Swindell in the 1970s. It includes a polarizing attachment that can project conoscopic images.

At some point, someone also purchased a set of 15 uniaxial, biaxial and optically active samples intended for classroom

Courtesy of Univ. Ariz./A. Peinado



The 550-nm Mueller matrix image, normalized to the first matrix element {0,0}; Mueller matrix elements are indexed from 0 to 3. The values near zero in elements {0,1}, {0,2}, {0,3}, {1,0}, {2,0}, and {3,0}, indicate low diattenuation (partial polarization) as would be expected of a transparent birefringent sample. The elements related to linear retardance at 45°, {1,1}, {1,3}, {3,1}, {3,3} are full of detail.

demonstrations. We use them to help students grasp important concepts of polarization and anisotropic materials with eye-catching and colorful images. The one labeled *Gips-bild* immediately catches everyone's attention. Although plain and nearly transparent on its own, it becomes a beautiful image of a butterfly cleverly represented in interference colors when viewed between crossed polarizers.

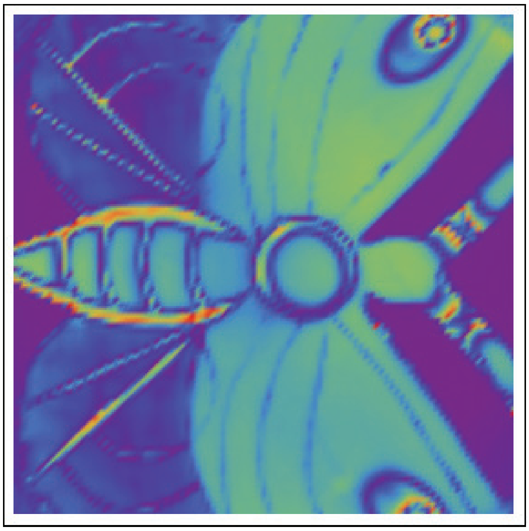
When: We have had the butterfly since the late 1970s, so we know that it was made prior to that time, perhaps much earlier.

Where: From the name, we conclude that it most likely came from Europe and probably Germany. Perhaps many other birefringent art objects were also produced by these methods.

The investigation

To learn more, we first contacted a virtual museum of Leitz and Leica projectors called the Pradoseum, which did not have information concerning the polarizing attachment or birefringent sample set. Leica Camera, the corporate descendant of Leitz, also could not help us, although they confirmed that the Prado 500 projector was one of their

The sample labeled *Gips-bild* immediately catches everyone's attention.



Courtesy of Univ. Ariz./A. Peinado

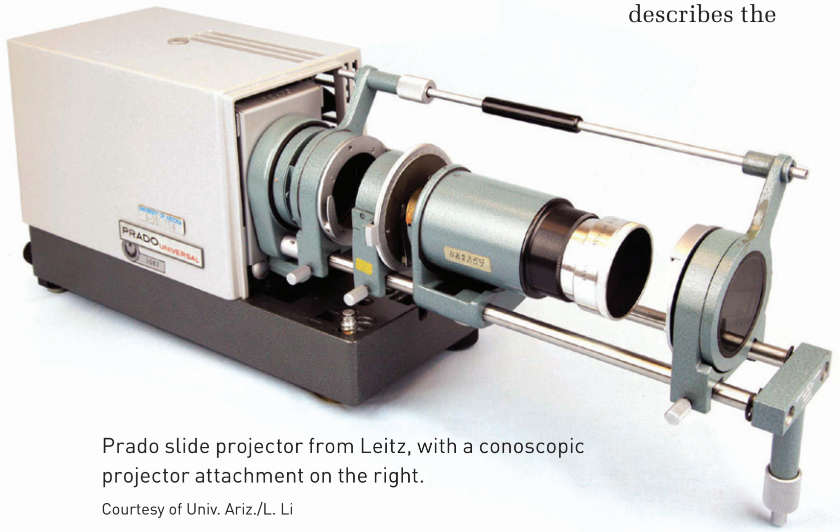
The 550-nm retardance magnitude and orientation: (Left) Principal retardance magnitude and (right) retardance orientation (both in degrees). Note that all parts of *Gips-bild* with nonzero thickness have a retardance orientation of ±45°, which is consistent with the butterfly being fabricated from a single piece of gypsum.

historic offerings and thought that certain attachments were a product of the micro division—now in a separate company, Microsystems Leica.

Finally, we talked to someone at Microsystems Leica. Unfortunately, though, we were once again out of luck and unable to get any further information on the gypsum butterfly. Additional Internet searches and other enquiries also proved fruitless.

To investigate *Gips-bild*'s fabrication techniques, we measured and analyzed Mueller matrix polarization images at the College's Polarization Laboratory. They were acquired at a series of wavelengths across the visible. The Mueller matrix of a sample is a 4×4 matrix, which describes the polarization properties of a sample, including diattenuation, retardance, polarizance and depolarization.

Our assessment of retardance magnitude and orientation showed us that all areas of *Gips-bild* with nonzero thickness have a retardance orientation of ±45°; thus, we believe the butterfly was fabricated from a single piece of gypsum.



Prado slide projector from Leitz, with a conoscopic projector attachment on the right.

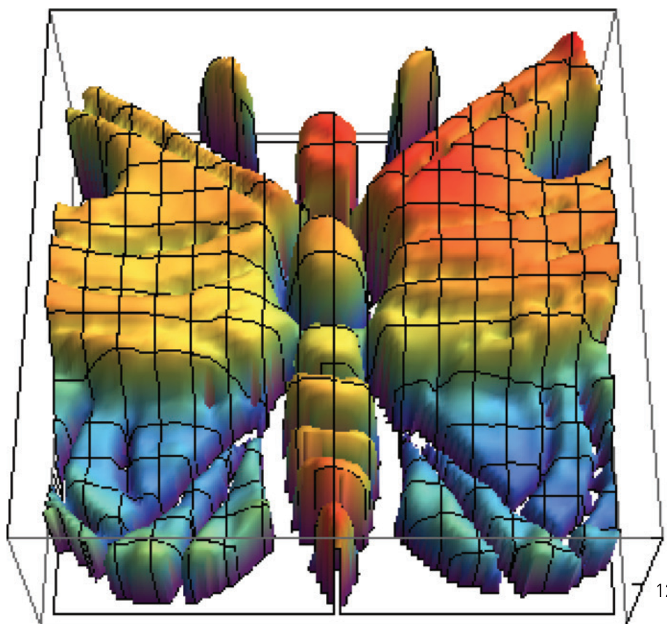
Courtesy of Univ. Ariz./L. Li

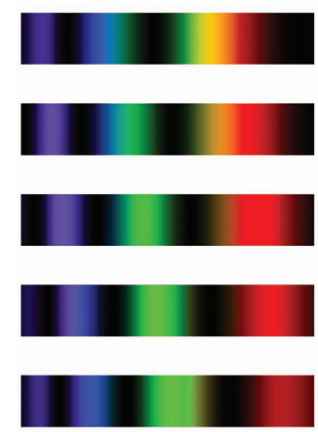
The analysis

The retardance magnitude variations outline and color the body of the butterfly. Therefore, the colorful pattern is due to the retardance magnitude variation and, consequently, thickness variations in a gypsum crystal.

The retardance magnitude data calculated from Mueller matrices are principal values of retardance, restricted to values between 0 and π radians, due to the limited range of the arctangent function. The Mueller matrix is a periodic function of retardance, so the actual retardance is not directly measured. However, by using the wavelength variation of retardance, we unwrapped the principal retardance to assign the proper order of $n\,\pi$ radians, yielding a retardance spectrum at each pixel.

To convert retardance to thickness, we applied the Cauchy dispersion





(Above, left) Thickness map of *Gips-bild*. (Above, right) Calculated transmission spectra for interference colors from the gypsum dispersion equation for several thicknesses.

Courtesy of Univ. Ariz./A. Peinado

function for the gypsum's birefringence in the visible spectrum:

$$\Delta n(\lambda) = 0.00903 + \frac{72.61}{\lambda^2} .$$

Then, we were able to fit, pixel by pixel, the thickness *t* to the pixel's 450- to 700-nm retardance spectrum resulting in the figure above that shows gypsum thickness. We also masked out very thin gypsum regions (retardance below 0.2 radians) and applied a 3×3 median filter for noise suppression.

The colorful blue and purple regions correspond to thickness variations from only 115 to 135 µm, corresponding to a retardance variation of 1,070 to 1,260 nm. The yellow regions are thinner, around 900 nm. These interference colors lie in the second and third order region of interference colors, as represented on the Michael-Levy chart.

To be continued . . .

The polarimetric data indicate that the butterfly was made by polishing a thin gypsum plate to produce interference colors in the range of 900 to 1,250 nm of retardance. We believe that a very fine, high-resolution method of polishing or material removal was used, since most of the color corresponds to a variation of only 20 µm.

Our investigations to date have not uncovered who fabricated the gypsum butterfly, the techniques used, where the work was performed, or the existence of other related pieces. But we haven't given up hope.

For all the intrepid scientists out there, we need your help in playing detective. Please send any information and insights to opn@osa.org. We hope to follow up with a short piece announcing that the case has been closed! OPN

Russell Chipman (rchipman@optics.arizona.edu) is a professor of optical sciences at the University of Arizona and a Fellow of OSA. Alba Peinado is a Ph.D. candidate at the departamento de física, Universitat Autònoma de Barcelona (UAB), Spain; she performed this work at the University of Arizona during a Predoctoral Research grant (BES-2010-031696, from the Spanish Ministerio de Economía y Competividad).

We believe that a very fine, high-resolution method of polishing or material removal was used, since most of the color corresponds to a variation of only 20 µm.